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Tillage and cropping sequence impacts on nitrogen cycling in dryland farming in eastern Montana, USA

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ABSTRACT

Information on N cycling in dryland crops and soils as influenced by long-term tillage and cropping sequence is needed to quantify soil N sequestration, mineralization, and N balance to reduce N fertilization rate and N losses through soil processes. The 21-yr effects of the combinations of tillage and cropping sequences was evaluated on dryland crop grain and biomass (stems + leaves) N, soil surface residue N, soil N fractions, and N balance at the 0–20 cm depth in Dooley sandy loam (fine-loamy, mixed, frigid, Typic Argiboroll) in eastern Montana, USA. Treatments were no-tilled continuous spring wheat (*Triticum aestivum* L.) (NTCW), spring-tilled continuous spring wheat (STCW), fall- and spring-tilled continuous spring wheat (FSTCW), fall- and spring-tilled spring wheat–barley (*Hordeum vulgare* L.) (1984–1999) followed by spring wheat–pea (*Pisum sativum* L.) (2000–2004) (FSTW-B/P), and spring-tilled spring wheat–fallow (STW-F). Nitrogen fractions were soil total N (STN), particulate organic N (PON), microbial biomass N (MBN), potential N mineralization (PNM), NH_4-N, and NO_3-N. Annualized crop grain and biomass N varied with treatments and years and mean grain and biomass N from 1984 to 2004 were 14.3–21.2 kg N ha^{-1} greater in NTCW, STCW, FSTCW, and FSTW-B/P than in STW-F. Soil surface residue N was 9.1–15.2 kg N ha^{-1} greater in other treatments than in STW-F in 2004. The STN at 0–20 cm was 0.39–0.96 Mg N ha^{-1}, PON 0.10–0.30 Mg N ha^{-1}, and PNM 4.6–9.4 kg N ha^{-1} greater in other treatments than in STW-F. At 0–5 cm, STN, PON, and MBN were greater in STCW than in FSTW-B/P and STW-F. At 5–20 cm, STN and PON were greater in NTCW and STCW than in STW-F, PNM and MBN were greater in STCW than in NTCW and STW-F, and NO_3-N was greater in FSTW-B/P than in NTCW and FSTCW. Estimated N loss through leaching, volatilization, or denitrification at 0–20 cm depth increased with increasing tillage frequency or greater with fallow than with continuous cropping and ranged from 9 kg N ha^{-1} yr^{-1} in NTCW to 46 kg N ha^{-1} yr^{-1} in STW-F. Long-term no-till or spring till with continuous cropping increased dryland crop grain and biomass N, soil surface residue N, N storage, and potential N mineralization, and reduced N loss compared with the conventional system, such as STW-F, at the surface 20 cm layer. Greater tillage frequency, followed by pea inclusion in the last 5 out of 21 yr in FSTW-B/P, however, increased N availability at the subsurface layer in 2004.

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1. Introduction

Long-term dryland conventional farming systems, such as spring-tilled spring wheat–fallow (STW-F), have resulted in the decline of soil total N (STN) by 30–50% of their original levels in the last 50–100 yr in the northern Great Plains, USA (Haas et al., 1957; Peterson et al., 1998). Intensive tillage increases the mineralization of STN (Bowman et al., 1999; Schomberg and Jones, 1999) and fallowing increases its loss by reducing the amount of plant residue N returned to the soil and increasing soil erosion (Black and Tanaka, 1997; Campbell et al., 2000). Although extending the fallow period compared with STW-F by reducing cropping intensity (e.g. one crop in 3 yr instead of one crop in 2 yr) increases soil water storage and crop yields (Eck and Jones, 1992; Aase and Pikul, 1995), increased soil water and temperature during fallow can also accelerate mineralization of STN (Haas et al., 1974). As a result, the conventional farming system has become inefficient, uneconomical (Aase and Schaefer, 1996), and unsustainable due to reduced soil fertility and crop production, which resulted in increased dependence of producers on federal aids (Dhuyvetter et al., 1996).

Soil N storage under dryland cropping systems remains a challenge in the northern Great Plains because of lower crop residue N returned to the soil due to limited precipitation and

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shorter growing season (Campbell et al., 1989; Sainju et al., 2006, 2007b). Improved soil and crop management practices, such as reduced tillage and increased cropping intensity, however, can increase dryland STN and N fractions to a depth of 20 cm compared with the conventional practice, such as STW-F (Sherrod et al., 2003; Sainju et al., 2006, 2007b). The use of no-till has allowed producers to increase cropping intensity in the northern Great Plains (Aase and Pikul, 1995; Aase and Schaefer, 1996; Peterson et al., 2001) because no-till conserves surface residues and retains water in the soil profile more than conventional till (Farhani et al., 1998). As a result, soil water can be used more efficiently by crops in no-till (Deibert et al., 1986; Aase and Pikul, 1995), which can reduce or eliminate summer fallow by growing continuous crops (Farhani et al., 1998; Peterson et al., 2001). Similarly, crops grown in rotations or with shorter fallow periods often have higher annualized biomass N than those grown without rotation or with longer fallow periods (Copeland and Crookston, 1992; Halvorson et al., 2002). These management practices alter soil microbial activity and N mineralization due to changes in microbial biomass N (MBN) (Bonde and Rosswall, 1987; Bremner and Van Kissel, 1992) as a result of changes in soil moisture and temperature (Ross, 1987).

Increase in N storage in crop residue and soil is needed to reduce N losses through leaching, volatilization, surface runoff, erosion, and N_2O (a greenhouse gas) emission. Although N is harvested in crop grains, N in aboveground biomass (stems + leaves) is either harvested or returned to the soil. In contrast, N in belowground biomass (root) is recycled back to the soil. Information on soil N mineralization about the ability of soil to supply N in a growing season is needed to optimize N availability for crop growth so that the cost and rate of N fertilization can be reduced. For these reasons, a better understanding of N cycling in crop and soil is needed. Besides above- and belowground biomass N and soil surface residue N, some of the important parameters of soil N cycling are STN, particulate organic N (PON), MBN, potential N mineralization (PNM), NH_4-N, and NO_3-N. Since STN has a large pool size and inherent spatial variability, it takes long time (>5 yr for most soils) to measure changes in STN due to management practices (Franzluebbers et al., 1995). As a result, measurement of STN alone does not adequately reflect changes in soil productivity and nutrient status (Franzluebbers et al., 1995; Bezdicek et al., 1996). Measurement of biologically active fractions of STN that change rapidly with time (e.g. within a growing season), such as MBN and PNM, could better reflect changes in soil quality and productivity that alter nutrient dynamics due to immobilization-mineralization (Saffigna et al., 1989; Bremner and Van Kissel, 1992). These fractions can provide an assessment of changes in STN and potential N mineralization induced by management practices, such as tillage and cropping systems (Campbell et al., 1989; Sainju et al., 2006, 2007b). Similarly, PON has been considered as an intermediate fraction of N between active and slow fractions that also changes rapidly due to changes in management practices (Cambardella and Elliott, 1992). The NH_4-N and NO_3-N fractions have been considered as available pools of N for crop uptake or soil residual N after crop harvest that can be lost due to leaching, volatilization, or surface runoff (Wood et al., 1990; Sainju et al., 2007b).

Increased residue accumulation, followed by higher level of MBN, at the surface soil in no-till can enhance N immobilization (Zibilske et al., 2002), thereby resulting in a need for greater N fertilization rates to crops (Bronson et al., 2001). In contrast, N fertilization rates for optimal crop production are often reduced in rotations containing legumes compared with monoculture non-legume cropping systems (Heichel and Barnes, 1984). This could be partly explained by greater labile N fractions, such as MBN and PNM, or greater turnover rate of organic matter in diversified crop rotations (Franzluebbers et al., 1995). Wood et al. (1990) found that soil profile NO_3-N content decreased with increased cropping intensity due to greater N immobilization, less summer fallow, and greater amount of N removed by crops. Increasing fallow period can increase N loss below the root zone due to leaching and absence of crops to conserve N (Eck and Jones, 1992; Campbell and Zentner, 1993).

Because of the longer time needed to increase dryland N storage and soil productivity (Sherrod et al., 2003; Sainju et al., 2006), information on the effects of long-term tillage and cropping sequence on N cycling in crops and soils is often limited in the northern Great Plains. This study provided a unique opportunity to examine the effects of long-term (21 yr) tillage and cropping sequence on dryland soil N storage, N mineralization potential and availability, and N balance or N loss at the surface 20 cm layer in the northern Great Plains, USA. It was hypothesized that long-term (21 yr) reduced tillage frequency with increased cropping intensity would increase soil surface residue and N fractions and reduce N loss at the 0–20 cm depth through soil processes compared with the conventional STW-F. Since N cycling is related with C cycling, the effects of tillage and cropping sequence on C cycling have been reported by Sainju et al. (2007a). This study exclusively reports the effects of long-term tillage and cropping sequence on dryland crop and soil N cycling in the semiarid region in eastern Montana, USA. The objectives of the study were to: (1) quantify the 21-yr influence of combinations of tillage and cropping sequence on dryland crop grain and biomass (stems + leaves) N, soil surface residue N, and STN, PON, PNM, MBN, NH_4-N, and NO_3-N concentrations and contents at 0–5 and 5–20 cm depths and (2) estimate N balance or N loss at the surface 20 cm layer due to soil processes under dryland cropping systems in the semiarid northern Great Plains, USA.

2. Materials and methods

2.1. Site description and treatments

The experiment was started by Aase and Pikul (1995) in 1983. The experimental site was located 11 km north of Culbertson (48°33′N, 104°50′W) in eastern Montana, USA. The site is characterized by wide variations in mean monthly air temperature from −8 °C in January to 23 °C in July and August. The mean annual precipitation (105-yr average) is 340 mm, 70% of which occurs during the crop growing season (April–August) (Table 1). The soil is a Dooley sandy loam (fine-loamy, mixed, frigid, Typic Argiboroll) with 0–2% slope. The soil sampled in 1983 prior to the initiation of the experiment had 645 g kg^{-1} sand, 185 g kg^{-1} silt, 170 g kg^{-1} clay, 1.50 Mg m^{-3} bulk density, 16.8 Mg ha^{-1} organic C, and 6.2 pH at the 0–8 cm depth (Aase and Pikul, 1995).

Details of the experimental treatments and management were described by Aase and Pikul (1995) and Aase and Schaefer (1996). The treatments consisted of no-tilled continuous spring wheat (NTCW), spring-tilled continuous spring wheat (STCW), fall- and spring-tilled continuous spring wheat (FSTCW), fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004) (FSTW-B/P), and spring-tilled spring wheat–fallow. Spring wheat was planted annually in the spring in NTCW, STCW, and FSTCW. In FSTW-B/P, spring wheat–barley was the rotation from 1984 to 1999, where both spring wheat and barley were planted in the spring. In 2000, barley was replaced by pea, thereby forming spring wheat–pea rotation from 2000 to 2004 in FSTW-B/P. The STW-F represented the conventional farming system where spring wheat was planted in alternate year in the spring wheat–fallow sequence. Each phase

Table 1
Monthly and annual precipitation (mm) from 1984 to 2004 near the study site 11 km north of Culbertson, Montana, USA.

Year	April	May	June	July	August	Total April–August	Total annual
1984	8	21	52	6	9	96	198
1985	33	59	17	33	27	169	317
1986	18	80	64	93	100	354	449
1987	14	102	29	100	20	264	356
1988	16	25	45	18	11	114	236
1989	59	45	31	74	34	243	368
1990	16	55	63	54	40	228	282
1991	68	67	113	41	15	303	412
1992	73	30	103	48	65	318	401
1993	5	26	60	131	75	296	377
1994	16	54	114	54	12	249	302
1995	22	27	35	68	61	213	312
1996	11	39	49	88	0	187	346
1997	23	17	22	117	45	224	282
1998	8	27	77	82	23	217	395
1999	6	79	28	77	24	213	281
2000	20	28	120	163	10	341	488
2001	39	9	91	206	4	348	378
2002	13	32	85	46	38	214	291
2003	17	69	114	114	42	356	409
2004	20	73	30	84	64	270	378
105-yr average[a]	31	53	75	52	36	240	340

[a] The 105-yr average precipitation data were taken from Culbertson, MT, which is 11 km south of the study site.

of the crop rotation was present in every year. In STCW, plots were tilled with a sweep plow prior to spring wheat seeding to prepare a seedbed in the spring. In FSTCW and FSTW-B/P, plots were tilled with standard sweeps (0.45 m wide with medium crown) and rods (harrow) in the fall, followed by tandem disk tillage in the spring to prepare the seedbed. In STW-F, plots were tilled with tandem disk prior to seeding in the spring and sweep and rods during fallow periods as needed to control weeds. All tilled plots were cultivated to a depth of 10 cm. In NTCW, plots were left undisturbed, except for applying fertilizers and seeding in rows. Weeds in NTCW were controlled by applying preplant and postharvest herbicides and in other treatments by a combination of herbicides and sweep tillage to a depth of 10 cm as needed. Treatments were arranged in a randomized complete block with four replications. Individual plot size was 12 m × 30 m.

2.2. Crop management

The rates of N, P, and K fertilization to spring wheat, barley, and pea were broadcast in all treatments at the time of planting in the spring according to crop yield goals and protein content and soil test to a depth of 60 cm under dryland conditions. The crop yield goals and protein content were spring wheat, 2350 kg ha^{-1} and 13%; barley, 2400 kg ha^{-1} and 12.5%; and pea 1100 kg ha^{-1} and 20%, respectively (MSU/NDSU, 1997). Using soil NO_3-N level to a depth of 60 cm, N fertilization rates were adjusted every year to provide total (soil + fertilizer) N to spring wheat and barley at 70 kg N ha^{-1} in all treatments. Nitrogen fertilizer was applied as urea (46% N) and monoammonium phosphate (18% N, 46% P). For pea, N fertilizer was applied at 5 kg N ha^{-1} when monoammonium phosphate was applied as P fertilizer. The P fertilizer was applied at 56 kg P ha^{-1} as monoammonium phosphate and K fertilizer at 48 kg K ha^{-1} as muriate of potash (60% K) to all crops in all treatments every year based on the soil test. While the fertilizers were applied at the soil surface in no-tilled treatments, these were incorporated to a depth of 10 cm during plowing in tilled treatments. As a result, part of N applied as urea at the soil surface in no-tilled treatments could be lost through volatilization. The amount of N loss through such process was not known.

Spring wheat [cv. Lew (unknown source) from 1984 to 1996 and McNeal (Foundation Seed, Montana State University, Bozeman, Montana, USA) from 1997 to 2004] was planted at 74 kg ha^{-1} in April of every year using a double disk opener with a row spacing of 20–25 cm from 1984 to 1996 and a Versatile no-till drill from 1997 to 2004. Similarly, barley [cv. Hector (unknown source) from 1984 to 1996 and Certified Tradition (Busch Agricultural Resources, Fargo, ND, USA) from 1997 to 1999] at 84 kg ha^{-1} and pea [cv. Majoret (Macintosh Seed, Havre, MT, USA) from 2000 to 2004] at 160 kg ha^{-1} were planted exactly as spring wheat above. Growing season weeds were controlled with selective post emergence herbicides appropriate for each crop. Contact herbicides were applied at postharvest and preplanting and fallow plots were tilled with sweeps as needed (at least three times a year) to control weeds. From 1984 to 1993 and in 1995, grain and biomass (stems + leaves) yields of spring wheat, barley, and pea were determined by cutting bundle samples at 2.5 cm above the ground from five 1-m long rows from six areas in each plot in July and August each year (Aase and Pikul, 1995; Pikul and Aase, 1999). The bundle samples were dried, weighed, and threshed; from which grain and biomass (stems + leaves) yields were determined. In July and August, 1994 and from 1996 to 2004, grain yield was determined from a swath of 1.5 m wide × 10–30 m long with a combine harvester in central rows. Biomass yield was measured by harvesting plants from an area of 0.5 m × 1 m outside yield rows after separating grains from stems and leaves and oven-drying a subsample at 60 °C for 3 d. After determining grain and biomass yields, grain from the rest of the plot was removed with a combine harvester while biomass (stems + leaves) was returned to the soil. To estimate grain and biomass N, N concentrations in grains of spring wheat, barley, and pea were considered as 20.8, 19.4, and 39.6 g N kg^{-1}, respectively, and in biomass (stems + leaves) as 12.8, 10.8, and 27.2 g N kg^{-1}, respectively (unpublished data). Since long-term data (1984–2004) for grain and biomass N concentrations in spring wheat, barley, and pea for the experiment were not available, these values were estimated for each crop from a different near-by experiment where N concentrations (6-yr averages) were determined. Grain and biomass N contents (Mg N ha^{-1}) were calculated by multiplying grain and biomass yields by their N concentrations. Belowground (root) biomass N was estimated by multiplying aboveground biomass (stems + leaves) N by a factor of 0.057 for spring wheat, 0.053 for barley, and 0.060 for pea (unpublished data from an another near-by experiment from where root N concentration for each crop was determined as above). Grain and biomass N were annualized by averaging crop N contents within the phases of the rotation in a year. For STW-F, grain and biomass N were annualized by dividing spring wheat grain and biomass N by 2, since crops were absent during the fallow phase of the rotation.

2.3. Residue and soil sample collection and analysis

In October 2004, 4–6 wk after fall tillage in FSTCW and FSTW-B/P or 8–10 wk after crop harvest in all treatments, soil surface residue samples were collected from five 30 cm × 30 cm areas randomly in the central rows of the plot, composited, washed with water to remove soil, and dried in the oven at 60 °C to obtain dry matter weight. Samples were removed from the soil surface by using iron frames, placed in a bucket of water, and residues floating in water were removed after washing several times. After drying, samples were ground to pass a 1 mm screen prior to C and N analysis. Immediately after removing the residue, soil samples were collected with a hand probe (5 cm inside diameter) from the 0–20 cm depth from five places in the central rows of each plot, separated into 0–5 and 5–20 cm depths, and composited within a depth. Samples were air-dried, ground, and sieved to 2 mm for determining N fractions. Two separate soil cores (5 cm inside diameter) were taken from 0–5 and 5–20 cm depths and composited within a depth to determine bulk density. Bulk density of two composited cores was determined by dividing mass of the oven-dried soil at 105 °C by their probe diameter and soil depth.

Total C and N concentrations (g C or N kg^{-1}) in soil surface residue were determined by using a dry combustion C and N analyzer (LECO Corp., St Joseph, MI). Nitrogen content (kg N ha^{-1}) in the residue was determined by multiplying dry matter weight by N concentration. The STN concentration in soil samples was determined by using the C and N analyzer as above after grinding the soil sample to <0.1 mm. For determining PON, 10 g soil was dispersed with 30 mL of 5 g L^{-1} sodium hexametaphosphate by shaking for 16 h and the solution was poured through a 0.053 mm sieve (Cambardella and Elliott, 1992). The solution that passed through the sieve and contained mineral associated and water soluble N was dried at 50 °C for 3–4 d and total N concentration was determined by using the analyzer as above. The PON concentration was determined by the difference between STN in whole-soil and that in the particles that passed through the sieve.

The PNM in air-dried soils was determined by the method modified by Haney et al. (2004). Two 10 g soils were moistened with water to 50% field capacity [0.25 m^3 m^{-3} (Aase and Pikul, 2000)] and incubated in a 1 L jar at 21 °C for 10 d. At 10 d, one container was removed and extracted with 50 mL of 2 M KCl for 1 h. The NH_4-N and NO_3-N concentrations in the extract were determined by using the autoanalyzer (Lachat Instrument, Loveland, CO). The PNM concentration was determined by the difference between the sum of NH_4-N and NO_3-N concentrations before and after incubation. The other container with moist soil was subsequently used for determining MBN by the modified fumigation–incubation method for air-dried soils (Franzluebbers et al., 1996). This container was incubated twice because MBN determination needed moist soil and mineralizable C was flushed out during the first incubation (Franzluebbers et al., 1996). The moist soil was fumigated with ethanol-free chloroform for 24 h and incubated for 10 d at 21 °C, after which NH_4-N and NO_3-N concentrations were determined as above after extracting with KCl. The MBN was calculated by the difference between the sum of NH_4-N and NO_3-N concentrations in the sample before and after fumigation–incubation and divided by a factor of 0.41 (Voroney and Paul, 1984). The NH_4-N and NO_3-N concentrations determined in the nonfumigated–nonincubated samples were used as available fractions of N.

The contents (Mg N ha^{-1} or kg N ha^{-1}) of STN, PON, PNM, MBN, NH_4-N, and NO_3-N at 0–5 and 5–20 cm depths were calculated by multiplying their concentrations (g N kg^{-1} or mg N kg^{-1}) by bulk density for each treatment and thickness of the soil layer. The total contents at 0–20 cm were determined by summing the contents at 0–5 and 5–20 cm.

2.4. Data analysis

Data for annualized crop grain and biomass N as influenced by treatments were analyzed using the MIXED procedure of SAS with year considered as the repeated measure variable (Littell et al., 1996). Treatment was considered as the fixed effect and replication as the random effect. Data for STN, PON, PNM, MBN, NH_4-N, and NO_3-N concentrations in 2004 were analyzed exactly as above by replacing year by soil depth as the repeated measure variable. Data for soil surface residue C and N and STN, PON, PNM, MBN, NH_4-N, and NO_3-N contents at each soil depth were analyzed using the MIXED procedure with treatment as the fixed effect and replication as the random effect. Since each phase of crop rotation was present in every year, data for both phases and averaged across phases of the crop rotation in FSTW-B/P and STW-F were used for the analysis. Means were separated by using the least square means test when treatments were significant (Littell et al., 1996). For determining the effect of tillage on grain and biomass N, soil surface residue N, and soil N fractions in the continuous spring wheat system, orthogonal contrast was used to compare the mean of NTCW vs. the mean of (STCW + FSTCW)/2 (Littell et al., 1991). Statistical significance was evaluated at $P \leq 0.05$, unless otherwise stated.

3. Results and discussion

3.1. Precipitation

The crop growing season precipitation (April–August) was above the 105-yr average in 11 out of 21 yr (Table 1). While precipitation in April was above the average in 5 out of 21 yr, above-average precipitation in May and August occurred in 9 out 21 yr, in June in 7 out of 21 yr, and in July in 15 out of 21 yr. Precipitation in May–June, the active crop growing period, is critical for the growth and production of dryland crops.

3.2. Crop grain and biomass nitrogen

Annualized crop grain and biomass N varied with years and treatments (Fig. 1). In 9 out of 21 yr (1986, 1987, 1992–1994, 1997, 2000, 2002, and 2004), grain and biomass N were greater in NTCW, STCW, FSTCW, and FSTW-B/P than in STW-F (Fig. 1). In 1986, 1987,

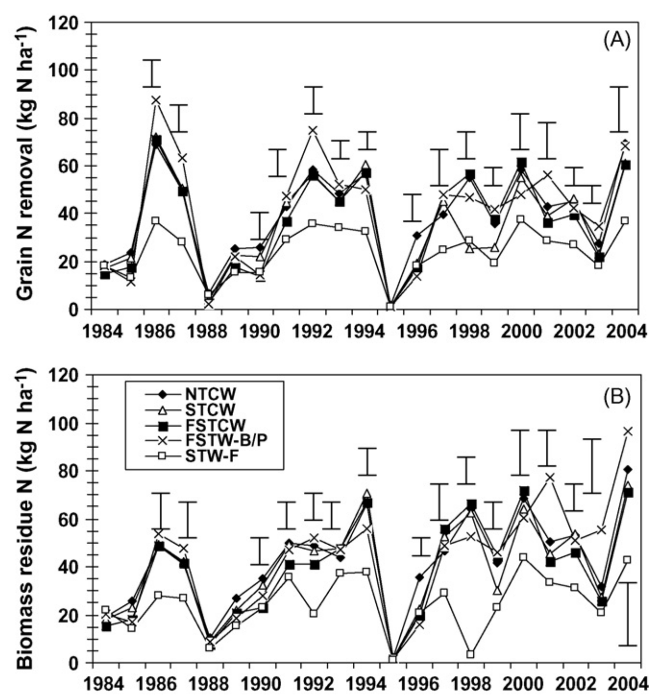

Fig. 1. Effects of tillage and cropping sequence on annualized (A) grain N removal and (B) biomass (stems + leaves) residue N of spring wheat, barley, and pea from 1984 to 2004 at the study site 11 km north of Culbertson, MT, USA. FSTCW represents fall- and spring-tilled continuous spring wheat; FSTW-B/P, fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004); NTCW, no-tilled continuous spring wheat; STCW, spring-tilled continuous spring wheat; and STW-F, spring-tilled spring wheat–fallow. Bars above or below grain N removal or biomass residue N in a year represents LSD at P = 0.05.

1992, and 2001, grain N was greater in FSTW-B/P and in 1996 was greater in NTCW than in other treatments (Fig. 1A). Similarly, in 2001 and 2003, biomass N was greater in FSTW-B/P and in 1996 was greater in NTCW than in other treatments (Fig. 1B). Grain and biomass N were minimal in all treatments in 1988 due to reduced plant growth as a result of lower growing season precipitation (April–August) (Table 1) and in 1995 when a hailstorm damaged the crop. Both grain and biomass N were relatively higher in 1986, 1992, and 2004 when the growing season precipitation was at least 112% of the long-term average. However, grain and biomass N did not always responded well with above-average growing season precipitation, such as in 2003 when grain and biomass N were relatively lower, even though growing season precipitation was 120% of the long-term average. Mean annualized grain and biomass N across years were 55–71% greater in NTCW, STCW, FSTCW, and FSTW-B/P than in STW-F (Table 2). Tillage, however, did not influence grain and biomass N in the continuous spring wheat system.

Variations in grain and biomass yields of dryland crops and their N contents due to annual differences in growing season precipitations in the northern Great Plains, USA were well known (Aase and Pikul, 1995; Halvorson et al., 2002; Lenssen et al., 2007a,b). Although grain and biomass N in NTCW amounted to 85% of those in STW-F in the crop year, annualized grain and biomass N in STW-F remained lower because of absence of crops during the fallow year. Similar results of lower annualized crop grain and biomass yields in crop-fallow than in continuous cropping, regardless of tillage, in dryland cropping systems of the northern and central Great Plains were reported by various researchers (Aase and Pikul, 1995; Halvorson et al., 2002; Sainju et al., 2006). The non-significant effect of tillage in grain and biomass N in the continuous spring wheat system (Table 2) suggests that no-till may be as good as conventional till in producing grain and biomass N. The no-till can increase soil water storage which results in similar or greater grain and biomass yields and N content than conventional till in the dryland cropping systems of the central and northern Great Plains (Miller et al., 2002; Halvorson et al., 2000; Lenssen et al., 2007a,b). Other researchers have found that tillage had no effect on grain and biomass yields or N contents in dryland crops and that cropping intensity was more important than tillage in affecting crop yields in the northern Great Plains (Halvorson et al., 2002; Sainju et al., 2006, 2007b; Lenssen et al., 2007a,b). Still others have reported that lack of increased crop yields and N uptake in no-tilled compared with tilled treatments was due to reduced N availability as a result of N immobilization by crop residue at the soil surface, even though no-till increased soil water content (Unger and McCalla, 1980; Peterson et al., 1996; Power and Peterson, 1998). Although barley and pea produced similar or lower grain and biomass N than spring wheat (Lenssen et al., 2007b), greater annualized grain N in 1986, 1987, and 1992, or greater grain and biomass N in 2001 and 2003 in FSTW-B/P than in NTCW, STCW, and FSTCW (Fig. 1) was probably a result of either rotation effect (spring wheat–barley rotation from 1984 to 1999) due to reduced incidences of diseases and pests or to beneficial effect of pea residue (spring wheat–pea rotation from 2000 to 2004) that contained higher N concentration and enriched soil N (Miller et al., 2002). The mean annualized grain and biomass N across years in FSTW-B/P was, however, not different from other treatments, except STW-F (Table 2).

Estimated mean annualized crop belowground biomass (root) N was 2.9, 2.7, 2.7, 2.7, and 1.7 kg N ha^{-1} for NTCW, STCW, FSTCW, FSTW-B/P, and STW-F, respectively. Belowground biomass N followed trends similar to grain and aboveground biomass (stems + leaves) N and were greater in other treatments than in STW-F. Absence of crops during fallow probably reduced belowground biomass N in STW-F, similar to grain and aboveground biomass N.

3.3. Soil surface residue nitrogen

Soil surface residue N content in 2004 was greater in NTCW, STCW, FSTCW, and FSTW-B/P than in STW-F, similar to grain and biomass N (Table 3). Surface residue N was greater in barley/pea phase than in wheat phase in FSTW-B/P, which is also greater than in other treatments. Similarly, surface residue N was greater in wheat phase than in fallow phase in STW-F. Surface residue C/N ratio was greater in wheat phase than in barley/pea phase in FSTW-B/P.

Table 2
Effects of tillage and cropping sequence on mean annualized crop grain N removal and biomass (stems + leaves) residue N returned to the soil (averaged across years) at the study site 11 km north of Culbertson, Montana, USA.

Tillage and cropping sequence[a]	Mean annualized crop grain N removal (kg N ha^{-1})	Mean annualized crop biomass N (kg N ha^{-1})
NTCW	43.6a[b]	51.0a
STCW	40.4a	47.2a
FSTCW	40.6a	47.4a
FSTW-B/P	40.9a	48.9a
STW-F	26.1b	29.8b
P value	<0.001	<0.001
Contrast[c]		
NT vs. ST + FST in CW	3.1	3.7

[a] Tillage and cropping sequence are FSTCW, fall- and spring-tilled continuous spring wheat; FSTW-B/P, fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004); NTCW, no-tilled continuous spring wheat; STCW, spring-tilled continuous spring wheat; and STW-F, spring-tilled spring wheat–fallow.
[b] Numbers followed by different letters within a column are significantly different at $P \leq 0.05$ by the least square means test.
[c] Contrast is shown as difference in mean values of the treatments as [NTCW − (STCW + FSTCW)/2]. Abbreviations used in contrast statement are CW, continuous spring wheat; FST, fall and spring till; NT, no-till; and ST, spring till.

Table 3
Effects of tillage and cropping sequence on soil surface N residue content and C/N ratio in 2004 at the study site 11 km north of Culbertson, Montana, USA.

Tillage and cropping sequence[a]	Soil surface residue	
	N content (kg N ha^{-1})	C/N ratio
NTCW	22.0b[b]	57.7b
STCW	21.1bc	58.9b
FSTCW	23.2b	62.4b
FSTW-B/P	27.2ab	48.5c
FST(W)-B/P[c]	22.6b	71.6b
FSTW-(B/P)[c]	31.7a	25.3d
STW-F	12.0de	66.7b
ST(W)-F[c]	16.5cd	89.9a
STW-(F)[c]	7.4e	43.6c
P value	0.042	0.038
Contrast[d]		
NT vs. ST + FST in CW	−0.15	−2.9

[a] Tillage and cropping sequence are FSTCW, fall- and spring-tilled continuous spring wheat; FSTW-B/P, fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004); NTCW, no-tilled continuous spring wheat; STCW, spring-tilled continuous spring wheat; and STW-F, spring-tilled spring wheat–fallow.
[b] Numbers followed by different letters within a column are significantly different at $P \leq 0.05$ by the least square means test.
[c] Letters within the parenthesis represent crops in the rotation phase of the cropping sequence. Crops are B, barley; F, fallow; P, pea; and W, spring wheat.
[d] Contrast is shown as difference in mean values of the treatments as [NTCW − (STCW + FSTCW)/2]. Abbreviations used in contrast statement are CW, continuous spring wheat; FST, fall and spring till; NT, no-till; and ST, spring till.

Similarly, surface residue C/N ratio was greater in wheat phase than in fallow phase in STW-F, which is also greater than in other treatments. Surface residue N and C/N ratio were not influenced by tillage in the continuous spring wheat system.

The lower soil surface residue N in STW-F than in other treatments was probably due to reduced amount of crop biomass N returned to the soil (Table 2). The fallow period is a time of high microbial activity and decomposition of organic matter with no input of crop residue (Halvorson et al., 2002). As a result, rapid decomposition of residue N, followed by reduced N input during fallow could have reduced surface residue N in STW-F. However, non-significant difference in surface residue N among NTCW, STCW, and FSTCW or non-significant effect of tillage in the continuous spring wheat system (Table 3) suggests that tillage did not alter the rate of decomposition of soil surface residue N. This could be due to similar levels of biomass N returned to the soil among NTCW, STCW, and FSTCW (Fig. 1B, Table 2), because surface residue N in 2004 could be influenced by biomass N returned to the soil in that year. Sainju et al. (2006) also did not observe significant influence of 6 yr of tillage on dryland soil surface residue N in the northern Great Plains. The greater surface residue N or lower C/N ratio in barley/pea phase than in wheat phase in FSTW-B/P was due to higher N concentration in pea (14.7 g N kg^{-1}) than in spring wheat (6.4 g N kg^{-1}) residue. In contrast, greater surface residue N or C/N ratio in wheat phase than in fallow phase in STW-F was due to higher surface residue amount in wheat (3.29 Mg ha^{-1}) than in fallow (0.85 Mg ha^{-1}) phase. Because of higher surface residue N in continuous cropping than in crop-fallow, continuous cropping can conserve N in the residue better than crop-fallow.

3.4. Soil bulk density

Soil bulk density in 2004 did not differ among treatments and between phases of a rotation (Table 4). Tillage also did not influence bulk density in the continuous spring wheat system. Bulk density, however, was greater at 5–20 than at 0–5 cm. The lack of significant difference in bulk density among treatments even after 21 yr of tillage and cropping sequence under dryland farming is surprising whose reasons were not known. For conversion of mass (concentration) to volume (content) basis of soil N fractions, bulk density value for each individual treatment and soil depth was, however, used for the calculation.

Table 4
Effects of tillage and cropping sequence on soil bulk density at 0–5 and 5–20 cm depths in 2004 at the study site 11 km north of Culbertson, Montana, USA.

Tillage and cropping sequence[a]	Soil bulk density (Mg m^{-3})	
	0–5 cm	5–20 cm
NTCW	1.33a[b]	1.47a
STCW	1.34a	1.48a
FSTCW	1.36a	1.50a
FSTW-B/P	1.37a	1.53a
FST(W)-B/P[c]	1.36a	1.54a
FSTW-(B/P)[c]	1.37a	1.52a
STW-F	1.38a	1.52a
ST(W)-F[c]	1.36a	1.50a
STW-(F)[c]	1.39a	1.53a
P value	0.245	0.382
Contrast[d]		
NT vs. ST + FST in CW	−0.02	−0.02

[a] Tillage and cropping sequence are FSTCW, fall- and spring-tilled continuous spring wheat; FSTW-B/P, fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004); NTCW, no-tilled continuous spring wheat; STCW, spring-tilled continuous spring wheat; and STW-F, spring-tilled spring wheat–fallow.

[b] Numbers followed by different letters within a column are significantly different at $P \leq 0.05$ by the least square means test.

[c] Letters within the parenthesis represent crops in the rotation phase of the cropping sequence. Crops are B, barley; F, fallow; P, pea; and W, spring wheat.

[d] Contrast is shown as difference in mean values of the treatments as [NTCW − (STCW + FSTCW)/2]. Abbreviations used in contrast statement are CW, continuous spring wheat; FST, fall and spring till; NT, no-till; and ST, spring till.

3.5. Soil total nitrogen and particulate organic nitrogen

The STN concentration and content at 0–5 cm and content at 0–20 cm were greater in NTCW and STCW than in FSTW-B/P and STW-F and greater in FSTCW than in STW-F (Table 5). At 5–20 cm, STN was greater in NTCW, STCW, and FSTCW than in STW-F. The STN was not different between phases of the crop rotation in FSTW-B/P and STW-F. No-till increased STN concentration and content at 0–5 cm and content at 0–20 cm compared with tilled practices in the continuous spring wheat system. At 0–5 cm, PON concentration and content were greater in STCW than in other treatments, except NTCW. At 5–20 and 0–20 cm, PON was greater in NTCW and STCW than in STW-F. The PON was not different between phases of the crop rotation in FSTW-B/P and STW-F and between tilled and no-tilled practices in the continuous spring wheat system. Both STN and PON concentrations were greater at 0–5 than at 5–20 cm.

The lower STN and PON concentrations and contents in STW-F than in other treatments (Table 5) were probably due to reduced amount of above- and belowground crop biomass N. The mean annualized amount of aboveground crop biomass N was lower in STW-F than in other treatments (Table 2). Reduced amount of annualized crop residue N, followed by their increased decomposition due to fallow probably reduced STN in spring wheat–fallow compared with continuous spring wheat (Campbell et al., 1989; Sainju et al., 2006, 2007b). In contrast, greater STN and PON at 0–5 and 0–20 cm in NTCW and STCW than in FSTW-B/P likely resulted from decreased tillage frequency, followed by a difference in cropping sequence [continuous spring wheat vs. spring wheat–barley/pea] between treatments. While decreased soil disturbance due to reduced tillage frequency could have reduced mineralization of STN and PON, thereby increasing their levels (Franzluebbers et al., 1999), greater STN and PON with continuous spring wheat than in spring wheat–barley/pea could be related to residue quality, such as C/N ratio, that results in different decomposition rates of residues in the soil (Kuo et al., 1997). As shown in Table 3, C/N ratio of soil surface residue containing pea was lower than that containing spring wheat in FSTW-B/P. Residues of legumes, such as pea, with lower C/N ratio decompose more rapidly than those of nonlegumes, such as spring wheat, thereby resulting in lower STN level (Kuo et al., 1997). Greater STN in no-tilled than in tilled treatments in the continuous spring wheat system (Table 5) suggests that tillage indeed reduced soil N storage at the surface 20 cm layer. Power and Peterson (1998) and Wienhold and Halvorson (1998) also reported greater STN at 0–30 cm depth in no-tilled than in tilled treatments in the northern Great Plains, USA. Venterea et al. (2006) reported that soil N storage at 0–60 cm depth was not different between tilled and no-tilled treatments because of greater STN level at 0–30 cm layer in no-tilled treatments but greater level at 30–60 cm layer in tilled treatments. They reported that greater STN at 30–60 cm in tilled treatments was due to crop residue incorporation and root growth to a greater depth. An examination of dryland crop root growth and STN levels at 0–120 cm depth as influenced by tillage and cropping system in an another near-by experiment revealed that most of the crop root growth and differences in STN levels occurred at the surface 20 cm soil layer and that no difference in STN was found between no-tilled and tilled treatments at 20–120 cm depth. Therefore, it was

Table 5
Effects of tillage and cropping sequence on soil total N (STN) and particulate organic N (PON) concentrations and contents at the 0–20 cm depth in 2004 at the study site 11 km north of Culbertson, Montana, USA.

Tillage and cropping sequence[a]	STN concentration at soil depth ($g N kg^{-1}$)		PON concentration at soil depth ($g N kg^{-1}$)		STN content at soil depth ($Mg N ha^{-1}$)			PON content at soil depth ($Mg N ha^{-1}$)		
	0–5 cm	5–20 cm	0–5 cm	5–20 cm	0–5 cm	5–20 cm	0–20 cm	0–5 cm	5–20 cm	0–20 cm
NTCW	1.47a[b]	0.72a	0.47ab	0.12a	0.98a	1.58a	2.56a	0.31ab	0.27a	0.58a
STCW	1.36a	0.68a	0.54a	0.10a	0.91a	1.52a	2.43a	0.36a	0.22a	0.58a
FSTCW	1.22ab	0.65ab	0.34bc	0.08ab	0.83ab	1.47a	2.30ab	0.23bc	0.17ab	0.40b
FSTW-B/P	0.97bc	0.58bc	0.32bc	0.07ab	0.66bc	1.33ab	1.99bc	0.22bc	0.16ab	0.38b
FST(W)-B/P[c]	1.00bc	0.62ab	0.32bc	0.06ab	0.68bc	1.44a	2.12ab	0.22bc	0.15ab	0.37b
FSTW-(B/P)[c]	0.93bc	0.54bc	0.32bc	0.07ab	0.64bc	1.22ab	1.86bc	0.22bc	0.17ab	0.39b
STW-F	0.81c	0.47c	0.27c	0.04b	0.55c	1.05b	1.60c	0.19c	0.09b	0.28b
ST(W)-F[c]	0.99bc	0.52b	0.30bc	0.03b	0.67bc	1.13b	1.80bc	0.21bc	0.07b	0.29b
STW-(F)[c]	0.62c	0.41b	0.24c	0.05b	0.43c	0.96b	1.39c	0.17c	0.11b	0.27b
P value	0.003	0.025	0.015	0.054	0.004	0.035	0.003	0.009	0.045	0.012
Contrast[d]										
NT vs. ST + FST in CW	0.18*	0.06	0.03	0.03	0.11*	0.09	0.20*	0.02	0.08	0.09

[a] Tillage and cropping sequence are FSTCW, fall- and spring-tilled continuous spring wheat; FSTW-B/P, fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004); NTCW, no-tilled continuous spring wheat; STCW, spring-tilled continuous spring wheat; and STW-F, spring-tilled spring wheat–fallow.
[b] Numbers followed by different letters within a column are significantly different at $P \leq 0.05$ by the least square means test.
[c] Letters within the parenthesis represent crops in the rotation phase of the cropping sequence. Crops are B, barley; F, fallow; P, pea; and W, spring wheat.
[d] Contrast is shown as difference in mean values of the treatments as [NTCW − (STCW + FSTCW)/2]. Abbreviations used in the contrast statement are CW, continuous spring wheat; FST, fall and spring till; NT, no-till; and ST, spring till.
* Differences between treatments are significant at $P \leq 0.05$.

decided to evaluate the effects of tillage and cropping sequence on soil N storage and N fractions at 0–20 cm depth only. The similar levels of STN and PON between phases of the crop rotation in FSTW-B/P and STW-F suggest that rotation phases had little influence on soil N storage.

Since the original levels of STN and PON before the initiation of the experiment in 1983 were not known, N storage rates as influenced by treatments cannot be calculated. However, STN at 0–20 cm was greater from 0.39 $Mg N ha^{-1}$ (24%) in FSTW-B/P to 0.96 $Mg N ha^{-1}$ (60%) in NTCW than in the conventional practice (STW-F) after 21 yr (Table 5). This resulted in an additional STN content of 46 $kg N ha^{-1} yr^{-1}$ at 0–20 cm depth in NTCW compared with STW-F. Similar results were obtained with PON. This suggests that using improved management practices, such as NTCW, N can be stored in the soil by an additional amount of 46 $kg N ha^{-1} yr^{-1}$ compared with the conventional practice, such as STW-F under dryland cropping systems in the semiarid northern Great Plains, USA, primarily by reducing N loss. Greater soil N storage will probably reduce the long-term N fertilization rates for optimum crop production (provided that N mineralization potential is also increased) due to reduced N loss and improved environmental quality by reducing the potentials for N leaching and the emission of N_2O, a devastating greenhouse gas responsible for global warming.

3.6. Labile nitrogen fractions

The PNM concentration and content at 0–5 cm were not influenced by treatments (Table 6). At 5–20 cm, PNM was greater in STCW than in NTCW and STW-F, and greater in FSTW-B/P than in STW-F. At 0–20 cm, PNM content was greater in STCW than in NTCW, FSTW-B/P, and STW-F, and greater in NTCW, FSTCW, and FSTW-B/P than in STW-F. The MBN concentration and content at 0–5 cm and content at 0–20 cm were greater in STCW than in other treatments. At 5–20 cm, MBN was greater in STCW than in NTCW and STW-F. Both PNM and MBN were not different between phases of the crop rotation in FSTW-B/P and STW-F. The PNM was not influenced by tillage practices but MBN at 5–20 and 0–20 cm was lower in no-tilled than in tilled practices in the continuous spring wheat system.

The NH_4-N concentration and content at 0–5 and 5–20 cm were not influenced by treatments but the content at 0–20 cm was greater in FSTW-B/P than in other treatments (Table 7). Similarly, NO_3-N concentration and content at 0–5 cm were not influenced by treatments but the concentration and content at 5–20 cm and the content 0–20 cm were greater in FSTW-B/P than in NTCW and FSTCW and greater in STW-F than in NTCW or FSTCW. Both NH_4-N and NO_3-N concentrations and contents were not influenced by phases of the crop rotation in FSTW-B/P and STW-F. The NH_4-N concentration and content were not influenced by tillage practices but NO_3-N concentration and content at 5–20 cm were greater in tilled than in no-tilled practices in the continuous spring wheat system.

The greater PNM and MBN concentrations and contents at 5–20 and 0–20 cm in STCW than in NTCW (Table 6) suggest that reduced tillage, such as disk tillage in the spring, increased potential N mineralization and microbial N at the subsurface layer, probably by increasing residue incorporation into the soil to a greater depth. This is similar to that obtained by Sainju et al. (2007b) in dryland cropping systems in northern Montana, USA but was in contrast to results reported by various researchers (Franzluebbers et al., 1995; Doyle et al., 2004) who reported greater MBN in no-till than in conventional till under irrigated crops in Texas and Kansas, USA. Variations in soil water due to differences in rainfall and irrigation system (dryland vs. irrigated) and temperature among locations could have influenced turnover rates of crop residue N into MBN as influenced by tillage. When tillage was not conducted or its frequency increased, PNM and MBN were not different among NTCW, FSTCW, and FSTW-B/P. Either N immobilization due to residue accumulation at the soil surface in NTCW or excessive mineralization of the substrate due to increased tillage frequency in FSTCW and FSTW-B/P could have resulted similar PNM and MBN levels in these treatments that are lower than in STCW. Inclusion of legumes, such as pea, in FSTW-B/P also did not increase PNM and MBN compared with other treatments, except STW-F. This is probably because inclusion of pea in 5 out of 21 yr in the rotation

Table 6
Effects of tillage and cropping sequence on soil potential N mineralization (PNM) and microbial biomass N (MBN) concentrations and contents at the 0–20 cm depth in 2004 at the study site 11 km north of Culbertson, Montana, USA.

Tillage and cropping sequence[a]	PNM concentration at soil depth (mg N kg^{-1})		MBN concentration at soil depth (mg N kg^{-1})		PNM content at soil depth (kg N ha^{-1})			MBN content at soil depth (kg N ha^{-1})		
	0–5 cm	5–20 cm	0–5 cm	5–20 cm	0–5 cm	5–20 cm	0–20 cm	0–5 cm	5–20 cm	0–20 cm
NTCW	12.6a[b]	4.9bc	36.5b	8.7b	8.4a	10.7bc	19.1b	24.3b	19.2b	43.5b
STCW	14.2a	6.6a	64.3a	18.2a	9.5a	14.7a	24.1a	43.1a	40.3a	83.4a
FSTCW	15.0a	5.2abc	41.5b	12.2ab	10.2a	11.7abc	21.9ab	28.2b	27.4ab	55.6b
FSTW-B/P	10.1a	5.4ab	34.2b	12.2ab	6.9a	12.3ab	19.2b	23.5b	27.9ab	51.4b
FST(W)-B/P[c]	11.0a	5.6ab	39.0b	12.5ab	7.5a	12.9ab	20.4b	26.9b	28.8ab	55.7b
FSTW-(B/P)[c]	9.2a	5.1abc	29.3b	11.8ab	6.3a	11.7abc	18.9b	20.1b	27.0ab	47.1b
STW-F	9.0a	3.7c	31.3b	8.6b	6.1a	8.4c	14.5c	21.5b	19.6b	41.1b
ST(W)-F[c]	8.7a	3.8c	31.0b	8.0b	5.9a	8.6c	14.5c	21.1b	18.0b	39.1b
STW-(F)[c]	9.3a	3.6c	31.5b	9.2b	6.4a	8.2c	14.6c	21.9b	21.2b	43.1b
P value	0.152	0.043	0.025	0.032	0.145	0.034	0.007	0.018	0.033	0.001
Contrast[d]										
NT vs. ST + FST in CW	−2.0	−1.0	−16.4	−6.5*	−1.5	−2.5	−3.9	−11.4	−14.7*	−26.0**

[a] Tillage and cropping sequence are FSTCW, fall- and spring-tilled continuous spring wheat; FSTW-B/P, fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004); NTCW, no-tilled continuous spring wheat; STCW, spring-tilled continuous spring wheat; and STW-F, spring-tilled spring wheat–fallow.
[b] Numbers followed by different letters within a column are significantly different at $P \leq 0.05$ by the least square means test.
[c] Letters within the parenthesis represent crops in the rotation phase of the cropping sequence. Crops are B, barley; F, fallow; P, pea; and W, spring wheat.
[d] Contrast is shown as difference in mean values of the treatments as [NTCW − (STCW + FSTCW)/2]. Abbreviations used in the contrast statement are CW, continuous spring wheat; FST, fall and spring till; NT, no-till; and ST, spring till.
* Differences between treatments are significant at $P \leq 0.05$.
** Differences between treatments are significant at $P \leq 0.01$.

may not have reached equilibrium in increasing labile N fractions in FSTW-B/P under dryland condition. In contrast, decreased crop biomass N (Fig. 1B, Table 2), followed by higher microbial activity during fallow, likely reduced PNM in STW-F compared with other treatments, as reported by several researchers (Bonde and Rosswall, 1987; Bremner and Van Kissel, 1992; Sainju et al., 2007b).

The greater NH_4-N and NO_3-N concentrations and contents in FSTW-B/P than in NTCW and FSTCW (Table 7) were likely a result of inclusion of pea, with higher N concentration than spring wheat, in the cropping sequence. Studies suggest that pea residue had N concentration around 27 g kg^{-1} compared with 13 g kg^{-1} in spring wheat residue (Lenssen et al., 2007b). Since PNM and MBN were similar to or lower in FSTW-B/P than in STCW (Table 6), greater NH_4-N and NO_3-N concentrations and contents in FSTW-B/P were probably a result of mineralization of N from fresh pea residue due to recent fall tillage, as soil samples were taken 4–6 wk after fall tillage in 2004. Non-significant differences in NH_4-N and NO_3-N concentrations and contents between phases of crop rotation in FSTW-B/P and STW-F were probably due to N fertilization to spring wheat during wheat phase and N mineralized from pea residue during pea phase in FSTW-B/P or mineralized from soil organic N

Table 7
Effects of tillage and cropping sequence on soil NH_4-N and NO_3-N concentrations and contents at the 0–20 cm depth in 2004 at the study site 11 km north of Culbertson, Montana, USA.

Tillage and cropping sequence[a]	NH_4-N concentration at soil depth (mg N kg^{-1})		NO_3-N concentration at soil depth (mg N kg^{-1})		NH_4-N content at soil depth (kg N ha^{-1})			NO_3-N content at soil depth (kg N ha^{-1})		
	0–5 cm	5–20 cm	0–5 cm	5–20 cm	0–5 cm	5–20 cm	0–20 cm	0–5 cm	5–20 cm	0–20 cm
NTCW	2.56a[b]	1.06a	6.24a	1.40c	1.70a[b]	2.33a	4.03b	4.15a	3.08c	7.22bc
STCW	1.94a	1.35a	6.12a	2.04abc	1.30a	3.00a	4.30b	4.10a	4.53abc	8.63abc
FSTCW	2.28a	0.98a	4.38a	1.59bc	1.55a	2.20a	3.75b	2.98a	3.58bc	6.63c
FSTW-B/P	3.88a	1.83a	7.25a	2.64a	2.65a	4.20a	6.85a	4.90a	6.05a	11.00a
FST(W)-B/P[c]	3.03a	1.96a	6.91a	2.69a	2.06a	4.53a	6.59a	4.70a	6.21a	10.91a
FSTW-(B/P)[c]	4.73a	1.70a	7.59a	2.58ab	3.24a	3.87a	7.11a	5.20a	5.89ab	11.09a
STW-F	1.58a	1.59a	6.60a	2.19ab	1.08a	3.62a	4.70b	4.53a	5.00ab	9.52ab
ST(W)-F[c]	1.84a	1.37a	6.99a	2.17ab	1.25a	3.08a	4.35b	4.75a	4.88ab	9.63ab
STW-(F)[c]	1.31a	1.81a	6.20a	2.23ab	0.91a	4.16a	5.07ab	4.31a	5.12ab	9.43ab
P value	0.275	0.194	0.152	0.025	0.172	0.117	0.002	0.100	0.032	0.019
Contrast[d]										
NT vs. ST + FST in CW	0.45	−0.11	0.99	−0.42*	0.28	−0.27	0.1	0.61	−0.98*	−0.41

[a] Tillage and cropping sequence are FSTCW, fall- and spring-tilled continuous spring wheat; FSTW-B/P, fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004); NTCW, no-tilled continuous spring wheat; STCW, spring-tilled continuous spring wheat; and STW-F, spring-tilled spring wheat–fallow.
[b] Numbers followed by different letters within a column are significantly different at $P \leq 0.05$ by the least square means test.
[c] Letters within the parenthesis represent crops in the rotation phase of the cropping sequence. Crops are B, barley; F, fallow; P, pea; and W, spring wheat.
[d] Contrast is shown as difference in mean values of the treatments as [NTCW − (STCW + FSTCW)/2]. Abbreviations used in the contrast statement are CW, continuous spring wheat; FST, fall and spring till; NT, no-till; and ST, spring till.
* Differences between treatments are significant at $P \leq 0.05$.

Table 8
Effects of tillage and cropping sequence on estimated N balance or N loss as a result of N fertilization rate, total crop grain N removal from 1984 to 2004, soil surface residue N in 2004, and soil total N (STN) content at the 0–20 cm depth during the initiation of the study in 1983 and after 21 yr in 2004 at the study site 11 km north of Culbertson, MT.

Tillage and cropping sequence[a]	Initial STN content in 1983 (A) (kg N ha^{-1})	Total N fertilization rate from 1984 to 2004 (B) (kg N ha^{-1})	Total crop grain N removal from 1984 to 2004 (C) (kg N ha^{-1})	Soil surface residue N in 2004 (D) (kg N ha^{-1})	Final STN content in 2004 (E) (kg N ha^{-1})	Estimated N balance or N loss from 1984 to 2004[b] (kg N ha^{-1})
NTCW	2600a[c]	1046a	916a	22a	2560a	192d
STCW	2600a	1046a	848a	22a	2430a	390c
FSTCW	2600a	1046a	853a	23a	2300a	516b
STW-F	2600a	501b	548b	12b	1600b	965a

[a] Tillage and cropping sequence are FSTCW, fall- and spring-tilled continuous spring wheat; NTCW, no-tilled continuous spring wheat; STCW, spring-tilled continuous spring wheat; and STW-F, spring-tilled spring wheat–fallow.
[b] N balance = Columns (A) + (B) + (D) − (C) − (E).
[c] Numbers followed by different letters within a column are significantly different at $P \leq 0.05$ by the least square means test.

during fallow phase in STW-F. Similarly, greater NO_3-N concentration and content in tilled than in no-tilled practices in the continuous spring wheat system was probably due to mineralization of residue and soil organic N. Halvorson et al. (2000) noted that soil NO_3-N content was greater in tilled than in no-tilled system in the northern Great Plains, USA. Sainju et al. (2007b) also reported greater NO_3-N content in conventional till with pea and lentil in rotation with spring wheat than in NTCW. Similarly, increased NO_3-N concentration and content in STW-F than in NTCW or FSTCW was probably a result of fallow that conserved soil water and increased N mineralization. Fallowing can increase soil water storage and NO_3-N content due to mineralization of soil organic N (Eck and Jones, 1992), but extending fallow period can increase N loss below the root zone due to leaching and absence of crops to conserve N (Eck and Jones, 1992; Campbell and Zentner, 1993).

3.7. Nitrogen balance

Differences in total N fertilization rates to crops among treatments from 1984 to 2004, grain N removal, soil surface residue N, and STN levels in 2004 have led to calculate estimated N balance or N loss from the dryland agroecosystem (Table 8). Since barley was replaced by pea in 2000 in FSTW-B/P, this cropping sequence may not have reached equilibrium in the agroecosystem N cycling. As a result, FSTW-B/P was not used in the calculation of estimated N balance. Nitrogen fertilization rate was lower in STW-F than in other treatments because the fertilizer was applied to spring wheat once in 2 yr during the crop phase. The initial STN level in 1983 was estimated by dividing soil organic C level (Aase and Pikul, 1995; Sainju et al., 2007a) by an estimated C/N ratio of 10.5. Nitrogen balance for each treatment was calculated by deducting the sum of total crop grain N removal from 1984 to 2004 and final STN level in 2004 from the sum of initial STN level in 1983, total N fertilization rate from 1984 to 1994, and soil surface residue N in 2004 (Table 8).

Estimated N balance or N loss from 1984 to 2004 increased as tillage frequency increased and cropping sequence changed from continuous spring wheat to spring wheat–fallow (Table 8). The N loss ranged from 192 kg N ha^{-1} in 21 yr (or 9 kg N ha^{-1} yr^{-1}) in NTCW to 965 kg N ha^{-1} (or 46 kg N ha^{-1} yr^{-1}) in STW-F. Power and Peterson (1998) have reported a gain of 9–16 kg N ha^{-1} yr^{-1} in no-tilled treatments to a loss of 26–47 kg N ha^{-1} yr^{-1} in tilled treatments in dryland soils at 0–30 cm depth. They suspected that N gain in no-tilled treatments was due to nonsymbiotic N fixation but N loss in tilled treatments was due to N leaching. They also reported that applied fertilizer N was retained more to a soil depth of 1 m in no-tilled than in tilled treatments. As tillage frequency increased, soil mineral N levels may have increased due to increased N mineralization from soil organic matter and crop residue (Halvorson et al., 2000), which probably led to increased N loss, primarily by leaching, volatilization, denitrification, or N_2O emission. Although N fertilization rate was lower, greater N loss in STW-F than in other treatments was probably due to greater soil mineral N content during fallow due to increased soil organic matter mineralization as a result of increased soil moisture and temperature (Haas et al., 1974; Eck and Jones, 1992) and absence of crops to conserve soil mineral N (Eck and Jones, 1992; Campbell and Zentner, 1993). It has been predicted that NO_3-N loss due to leaching is minimal under annual cropping system with normal precipitation in semiarid eastern Montana (Aase and Siddoway, 1982). Results, however, showed that over years, N loss could be significant even in no-tilled annual cropping systems in the semiarid regions and more so when lands are kept under fallow. Many years of summer fallow and extended fallow period can increase leaching loss of soil NO_3-N in the dryland cropping system (Eck and Jones, 1992; Campbell and Zentner, 1993). It was suspected that these losses could have occurred mainly during spring, summer, and fall during inactive growth of plants, such as before planting, after harvest, or during fallow when residual soil N level is higher, followed by periods of intense rainfall that increased water movement in the soil. The N leaching loss could be lower during winter, especially in Montana, USA, when grounds are frozen to more than a depth of 1.5 m and little water movement occurs.

4. Conclusions

Long-term no-till or spring till with continuous cropping increased dryland crop grain and biomass N, soil surface residue N, STN, PON, PNM, and MBN, and reduced N loss through soil processes compared with the conventional system, such as STW-F, due to reduced tillage and increased crop residue N returned to the soil. Increased tillage frequency, followed by a difference in cropping sequence from continuous spring wheat to spring wheat–barley/pea, however, increased NH_4-N and NO_3-N contents, but reduced STN, especially at the surface soil. Similarly, STW-F increased NO_3-N content at the subsurface soil compared with NTCW and FSTCW. Tillage with cropping sequences containing legumes or fallow may increase dryland soil N availability and reduce the immediate N fertilization rates to succeeding crops; however, reduced tillage, such as no-till or spring till, with continuous cropping can increase surface residue N, soil N storage, and potential N mineralization compared with the conventional STW-F. This can improve soil productivity and reduce the long-term N fertilization rates, N loss, and soil erosion potential under dryland cropping systems in the semiarid regions. Long-term N losses even in NTCW and STCW could be significant and such losses could be increased by two- to five-fold by using the conventional STW-F system.

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